Soil carbon dioxide fluxes of a typical broad-leaved/Korean pine mixed forest in Changbai Mountain, China

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Abstract: The forest ecosystem plays an important role in the global carbon cycling. A study was conducted to evaluate soil CO_2 flux and its seasonal and diurnal variation with the air and soil temperatures by using static closed chamber technique in a typical broad-leaved/Korean pine mixed forest area on the northern slope of Changbai Mountain, Jilin Province, China. The experiment was carried out through the day and night in the growing season (from June to September) in situ and sample gas was analyzed by a gas chromatograph. Results showed that the forest floor was a large net source of carbon, and soil CO_2 fluxes had an obvious law of seasonal and diel variation. The soil CO_2 flux of broad-leaved/Korean pine mixed forest was in the range of 0.30–2.42 $\mu mol \cdot m^{-2} \cdot s^{-1}$ with the mean value of 0.98 $\mu mol \cdot m^{-2} \cdot s^{-1}$. An examination on the seasonal pattern of soil CO_2 emission suggested that the variability in soil CO_2 flux could be correlated with variations in soil temperature, and the maximum of mean CO_2 flux occurred in July ((1.27 $\pm$ 23%) $\mu mol \cdot m^{-2} \cdot s^{-1}$) and the minimum was in September ((0.50 $\pm$ 28%) $\mu mol \cdot m^{-2} \cdot s^{-1}$). The fluctuations in diel soil CO_2 flux were also correlated with changes in soil temperature; however, there existed a factor for a time lag. Soil CO_2 flux from the forest floor was strongly related to soil temperature and had the highest correlation with temperature at 6-cm depth of soil. Q_{10} values based on air temperature and soil temperature of different soil depths were at the ranges of 2.09 - 3.40.

Keywords: Soil CO_2 flux; Broad-leaved/Korean pine mixed forest; Q_{10} value; Changbai Mountain

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Introduction

Soil carbon dioxide (CO_2) flux plays a critical role in determining the carbon cycling of terrestrial ecosystems (Valetini *et al.* 2000), meanwhile, it is an important index of soil bioactivity, fertility and ventilation (Macfadyen 1970; Neilson *et al.* 1990; Reiners 1968). The production of soil CO_2 depends upon the amount of soil organic matter and its materialization rate, the number and activity of soil microorganisms, and the respiration of soil animals and plants. Obviously, CO_2 emission is the outcome of all factors including the bio-metabolism and biochemistry process, and so forth. Many factors can affect the rate of CO_2 emission, which contribute to soil biological process and biochemical reaction velocity (Zhang *et al.* 2001).

Atmospheric CO_2 is one of the most important greenhouse gases. CO_2 sources and sinks is one of the heated topics concerned with the studies on global environment changes and carbon cycling. However, there is little information in literature about the measurement of CO_2 emission from soils of terrestrial ecosystems based on a long-term experiment, especially in typical areas. The broad-leaved/Korean pine mixed forest is the zone vegetation of the eastern mountainous region of the northeast of China, which distributes in Changbai Mountain, Wanda Mountains, Zhangguangcai Mountains and Xiaoxingan Mountains. Although there was a great deal of information in literature on soil CO_2 flux from grassland (Cui *et al.* 2000; Frank *et al.* 2002; Mielnick *et al.* 2000; Sims *et al.* 2001; Zhou *et al.* 2003) and cropland (Nakadai *et al.* 2002; West *et al.* 2002; Zhou *et al.* 2002), studies on this aspect have not been thoroughly investigated. Early studies on CO_2 emission from woodland were reported in 1968 by Reiners (1968). A number of articles have been published and there was great progress in this field in China recently, but experimental sites were very limited. Studies were conducted only in a few of areas, for example, Beijing region (Jiang 1997a; 1997b; Fang *et al.* 1995; Fang *et al.* 2002; Sun *et al.* 1995), Qinling (Liu *et al.* 2003), Hainan island (Wu *et al.* 1997) and Qingzang tableland (Luo *et al.* 2000; Cheng and Luo 2003). The structure of soil is inhomogeneous, and soil organic carbon has an obvious spatial distribution characteristic in China (Wang *et al.* 2001), therefore it is necessary to conduct studies on soil CO_2 flux and organic matter conversion in inhomogeneous soil areas. In this paper, the characters of the CO_2 emission and its seasonal and diel variability were studied in a typical broad-leaved/Korean pine mixed forest in full growth season. It is important for evaluating the atmospheric CO_2 budget and understanding the law for CO_2 emission and the cause of global warming and effects of vegetation changes on atmospheric CO_2 concentration exactly (Zhao *et al.* 2002).

At present, the main experimental methods for studying

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soil CO_2 flux are dark static chamber technique (Nakano *et al.* 2004) and micrometeorological method (Griffis *et al.* 2004). Sample gas was analyzed by three approaches: alkaline solution absorption method, infrared CO_2 analyzer, and a gas chromatograph. Alkaline solution absorption method can bring a higher error because the emission of soil CO_2 is very little in one hour; the method of gas chromatograph is used in this study, which can conquer the defect of the former.

Materials and methods

Measurement site and soil

The study was conducted in the National Natural Reserve of Changbai Mountain, which was the region of a famous regional forest, and the broad-leaved/Korean pine mixed forest was the horizontal zonic vegetation of this area. The measurement sites were located in the eternal sample plot I (42°24'N, 128°28'E) of a typical broad-leaved/Korean pine mixed forest, which was set by the Opened Research Station of Changbai Mountain Forest Ecosystems, Chinese Academy of Sciences. The soil type of the experimental field belongs to the dark-brown earths formed by volcano ash, the topography is basatic mesa, and parent rock is loose volcano ash sand (Table 1). The mean annual precipitation is 760 mm, and the mean annual temperature is 4.9–7.3 °C. The climate type belongs to continental temperate mountainous climate affected by monsoon with a longer winter and a shorter summer. Frost-free period lasts 116d. Main tree species are as follows: *Pinus koraiensis*, *Tilia amurensis*, *Fraxinus madshuric*, *Betula costata*, *Quercus mongolica* and so forth. The coverage degree of under-wood and herbaceous plants is 40% approximately.

Table 1. Section and component of soil in the plot

Soil depth /cm	Component	C (%)	N (%)	C/N
0–3	Litter	-	-	-
3–9	Dark grew sod	2.76	0.240	11.5
9–12	Grey brown soil	0.33	0.049	6.7
12–24	Volcano ash, gravel sod	0.18	0.030	6.0
24–80 (50–60)	Volcano ash, gravel sod with stone.	(0.05)	(0.028)	(1.8)
80–140 (110–120)	Volcano ash, gravel sod	(0.05)	(0.053)	(0.9)

Notes: data were inferred from ref. (Han *et al.* 2000).

Flux measurement and techniques

The method of dark static chambers was adopted to gather the sample gas. The chambers are made of columnar opaque PVC (h=11.5 cm; Φ=15 cm). Sample gas was analyzed with a gas chromatograph. Five repetitions were made at one time. Sampling steps are as follows: (1) Select suitable experimental sites, and then put chambers on the soil surface, and press chambers tightly with soils; (2) Take sample gas of 100 mL from static chambers by an injector and inject gas into plastic bags (made by Academy of Research and Design of Guangming Chemical Industry, Chemical Industrial Ministry); (3) Take sample gas again from chambers accordingly after 45 min.

The experiment was conducted throughout the full growing season, from early June to late September. The experimental measurement was made at day and night continually in the calm and freeze days. The frequency is two days a month, and one day made 12 times (one time every 2 hours). The measurements were at the time of 6:00, 8:00, 10:00, 12:00, 14:00, 16:00, 18:00, 20:00, 22:00, 00:00, 02:00 and 04:00 hours. CO_2 was analyzed on a gas chromatograph (Shimadzu GC-14B) with a FID detector. FID only responds strongly on organic matter and does not react on inorganic components. Therefore, CO_2 needs to pass a Ni accelerant transformation apparatus, and be measured by the production of CH_4 through reaction with H_2. This process can be expressed with following reaction quotation:

$$CO_2 + 4H_2 \xrightarrow[380\ ^\circ C \pm 10\ ^\circ C]{Ni} CH_4 + 2H_2O$$

The temperature of gasifying chamber, separating column and detector are 380 °C, 150 °C and 65 °C respectively. N_2, H_2, and air were taken as the carrier, the combustion gas, and the combustion-supporting gas respectively in the measurement. The standard CO_2 (358 μmol·mol^{-1}) is provided by the National Standard Matter Research Center of China.

Air and soil temperature

Air temperature and soil temperature at the depths of 3 cm, 6 cm, 9 cm, and 12 cm were measured while collecting sample gases.

Flux calculation

The fluxes of CO_2 were calculated from the concentration change over the measurement period. It can be expressed as follows:

$$F = \frac{\Delta m}{A \cdot \Delta t} = \rho \frac{V}{A} \cdot \frac{P}{P_0} \cdot \frac{T_0}{T} \cdot \frac{\Delta C}{\Delta t} = \rho \cdot h \cdot \frac{P \cdot T_0 \cdot \Delta C}{P_0 \cdot T \cdot \Delta t} \quad (1)$$

where, F refers to gas flux (μ mol·m^{-2}·s^{-1}); Δm is the gas exchange mass (g); V, A and h are the virtual volume (m^3), bottom area (m^2) and height (m) of the static chamber; Δt is the time of gas exchange (s); ρ is the concentration of CO_2 under standard conditions (g·L^{-1}); ΔC stands for balance of gas exchange mixing rate (ug·g^{-1}); T_0 and P_0 are the air absolute temperatures and pressure under standard conditions; T(K) and P(Pa) are the air absolute temperatures and pressure when taking sample gas respectively. Microsoft excel was used for all statistical analyses.

Regression analyses and Q_{10} value calculation

Correlation and no-linear regression analyses were used to test the relation Eq. (2). The Q_{10} values were calculated according to Eq. (3), (Buchmann 2000).

$$y = \beta_0 \cdot e^{(\beta_1 \cdot T)} \tag{2}$$

$$Q_{10} = e^{10 \cdot \beta_1} \tag{3}$$

Results and discussion

Seasonal and diel variation of soil CO_2 flux

Soil CO_2 flux varied widely over a year in a typical broad-leaved/Korean pine mixed forest of Changbai Mountain (Table 2), which ranged from 0.30 μmol·m^{-2}·s^{-1} to 2.42 μmol·m^{-2}·s^{-1} with the mean value at 0.98 μmol·m^{-2}·s^{-1}. In full growing season (from July to August), the mean value order of soil CO_2 flux showed: July >August >June >September. The maximum and the minimum mean values of soil CO_2 flux occurred in summer (July, (1.27±23%) μmol·m^{-2}·s^{-1}) and autumn (September, (0.50 ±28%) μmol·m^{-2}·s^{-1}), respectively. The seasonal variation of soil CO_2 fluxes is related to the metabolic activities of plants and soil animals and microorganism. Because the main microorganism population mass varied throughout the season on the northern slope of Changbai Mountain (Xu *et al.* 1980), the trend of seasonal variation in endogenous respiration and soil enzyme activity changed often with the fluctuation of soil microorganism amount. Otherwise, soil animals, earthworm for example, had an effect on forest soil CO_2 flux (Broken *et al.* 2000). Soil animals' activities varied with seasonal variation. From Fig. 1, it is obvious that the curves of soil CO_2 flux with time have the similar characters in different months. Soil CO_2 fluxes reached their lowest value before the sunrise and their maximum occurred in the time from 14:00 to 16:00 approximately. The change of soil temperature at different layers was different from that of soil moisture during a day; therefore, the diel emission of CO_2 mainly was controlled by the temperature of various soil layers (Zhao *et al.* 2002).

Table 2. Seasonal variation of soil CO_2 fluxes in broad-leaved/Korean pine mixed forest.

Month	Soil CO_2 flux Mean /μmol·m^{-2}·s^{-1}	Soil CO_2 flux Range /μmol·m^{-2}·s^{-1}	*SD*	*CV* (%)
June	0.52	0.31 - 0.82	0.16	31.18
July	1.97	1.37 - 2.42	0.45	22.74
August	0.93	0.50 - 1.24	0.22	23.72
September	0.50	0.30 - 0.72	0.14	27.97

Notes: *Sd* and *CV* refer to standard deviation and coefficients of variation respectively

The relationship between soil CO_2 flux and temperature

Generally, soil temperatures are the principal controlling factor in mesic soil, only while extremes (wet or dry) of soil water content occurring, soil respiration rate tends to be reduced (Sjögersten *et al.* 2002). Many studies suggested that soil water content had very little effect on forest soil CO_2 flux in the area with enough precipitation (Drewitt *et al.* 2002; Shibistova *et al.* 2002). Based on the results mentioned above, our study mainly focused on understanding and finding the relationship between soil CO_2 fluxes and temperature. The results showed that soil CO_2 flux had a strong relationship with air temperature and soil temperature at different depths of soil in full growing season (Fig. 2). We conducted the correlation analysis of soil CO_2 flux with air temperature and soil temperature at different depths of soil (Table 3). From Fig. 2, it can be seen that soil CO_2 fluxes are higher under higher air temperature condition than under lower ambient temperature.

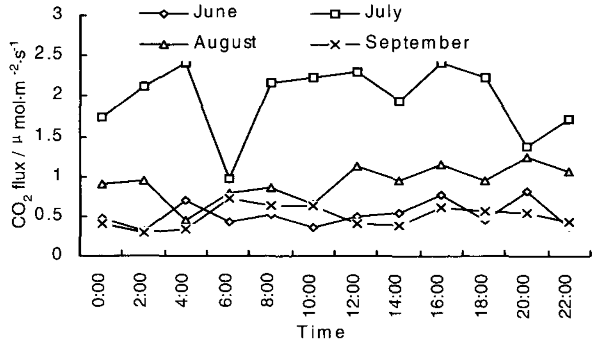

Fig. 1 Diel variation of soil CO_2 fluxes in the growth season

The soil CO_2 flux had much higher correlation with soil temperature than with air temperature. The reason is that microorganisms have the highest activities in the top layer of soil, which contribute the most to soil respiration. The results also showed that soil CO_2 flux from the forest floor was strongly related to soil temperature, having the highest correlation with the temperature at 6-cm soil depth (Table 3). This status may be contributed by the seasonal variation of microorganisms in the broad-leaved/Korean pine forest soil (Xu *et al.*1980). Soil temperature at the 6-cm soil depth can reflect effects of temperature on soil microorganisms accurately. Meanwhile soil temperature varies slowly because of the cover of litter-fall and the time lag of heat conduction.

Table 3. Relationships between soil CO_2 flux and temperature

Item		Q_{10} model	Q_{10}	R^2
	Air	$y = 0.2388e^{0.0736T}$	2.0876	0.5882
Soil	3 cm	$y = 0.1447e^{0.1154T}$	3.1709	0.687
depth	6 cm	$y = 0.1316e^{0.1225T}$	3.4042	0.6959
	9 cm	$y = 0.1295e^{0.1223T}$	3.3974	0.6511
	12 cm	$y = 0.1425e^{0.1181T}$	3.2576	0.6073

Notes: Q_{10} is the multiple of soil respiration increased while temperature increasing of 10 °C; R^2 refers to the coefficient of determination; *y* and *T* refer the soil CO_2 flux and the absolute temperature respectively

Liu *et al.* (1997) believed that soil CO_2 flux reduced along the latitude, however, if the site measured was located at a high altitude, which had a lower temperature than site with the same altitude, soil CO_2 flux would be lower.

Q_{10} value is most widely used to simulate the temperature response of soil respiration (Buchmann 2000; Janssens *et al.* 2003). In this study, the Q_{10} values were calculated according to air temperature and soil tempera-

tures at different soil depths (Table 3). Results showed that Q_{10} values were in the range of 2.09–3.40, the maximum occurred at 6-cm soil depth in the broad-leaved/Korean pine mixed forest in Changbai Mountain.

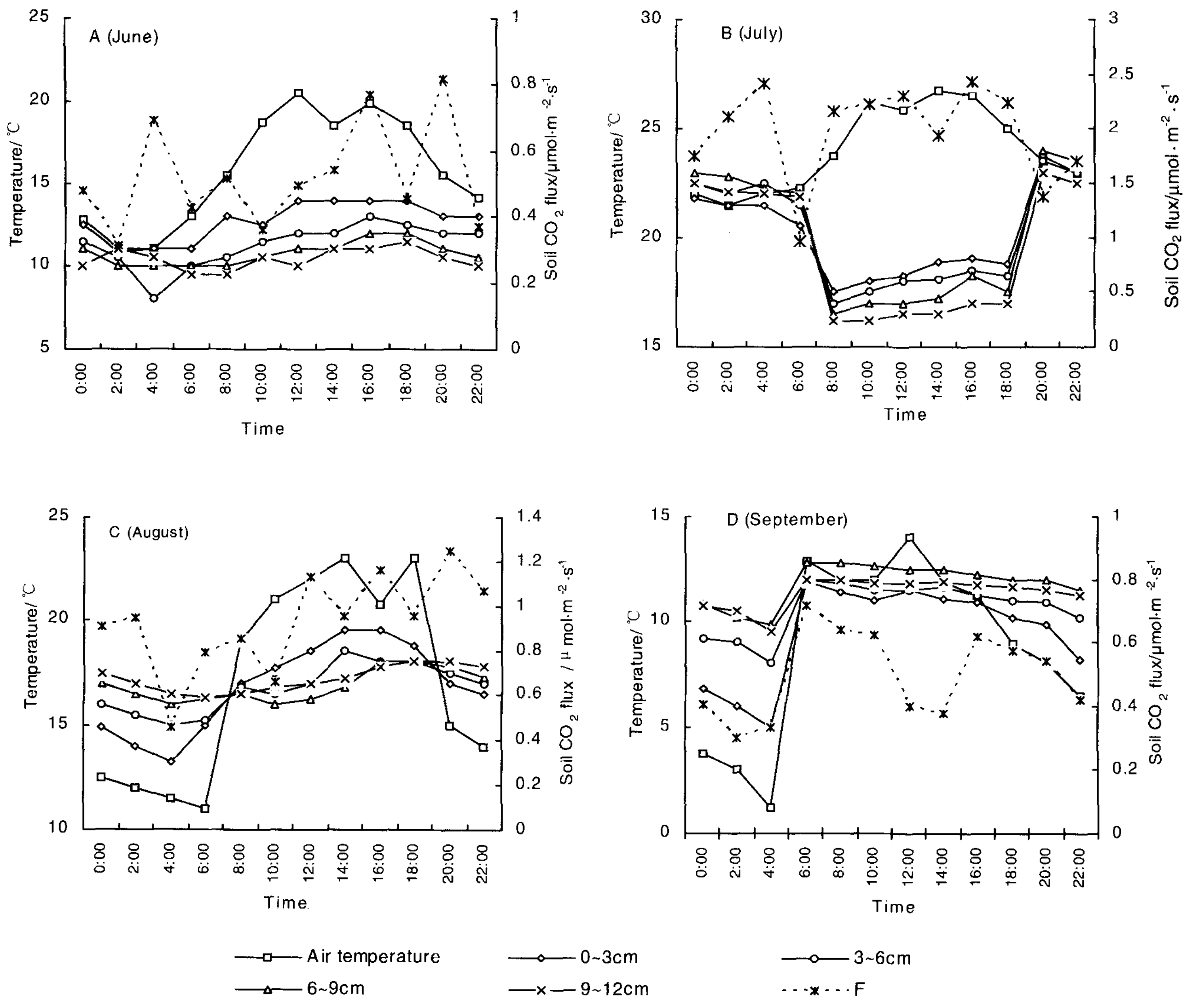

Fig. 2 Diel variations of soil CO_2 fluxes and temperatures of air and soil at different depths in the growth season

The correlation analysis (Table 3) showed that soil CO_2 emission rate had a higher correlation coefficient with air temperatures than with soil temperatures. The reason lies in the phenomena of CO_2 emission response lagging behind the time of atmospheric temperature occurring accordingly, because atmospheric temperatures transfer to the deeper soil layers to need some time (Zhao *et al.* 2002).

Conclusions

Measurements of soil CO_2 flux in the eternal plot of a typical broad-leaved/Korean pine mixed forest in Changbai Mountain in Northeastern China showed that the forest floor was a large net source of carbon. In the growth season, the forest soil CO_2 fluxes ranged from 0.30 to 2.42 μmol·m^{-2}·s^{-1}, with the mean value of 0.98 μmol·m^{-2}·s^{-1}. Carbon assimilation by forest-floor vegetation reduced the efflux by 12%–16% (Widen 2002), implying that this flux should not be neglected when evaluating carbon budgets in the forest ecosystems.

The forest soil CO_2 flux fluctuated obviously in full growth season and in one day, that is, CO_2 emissions from forest floor have an obvious seasonal and diel law. The phenomena were affected by temperatures of air and soil, especially soil temperature at 6-cm depth layer. In our measurement, the mean maximum and minimum of soil CO_2 flux occurred in summer (July, (1.27±23%) μ mol·m^{-2}·s^{-1}) and autumn (September, (0.50±28%) μ mol·m^{-2}·s^{-1}) seasonally, and in period of time of about 14:00–16:00, respectively. For understanding the relationship between the soil CO_2 flux and temperatures directly, we calculated Q_{10}

values which were in the range of 2.09–3.40, based on air temperature and soil temperature at different depth layers of 3 cm, 6 cm, 9 cm and 12 cm, respectively.

The results can provide a reference to construct carbon budgets in similar ecosystems in growth season. However, some researches reported that the terrestrial surface of high latitude emited CO_2 even in winter (Fang 1998; Mariko *et al.* 2000). So for understanding forest soil CO_2 flux exactly, further research should to be done in this area.

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